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Shock Experiments on Pre-Compressed Fluid Helium and Hydrogen

J. Eggert

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Shock Experiments on Pre-Compressed Fluid Helium and Hydrogen

51st Annual Meeting of the Divislon of Plasma Physics,
Atlanta, GA
5 November, 2009

Lawrence Livermore National Laboratory

Jon Eggert

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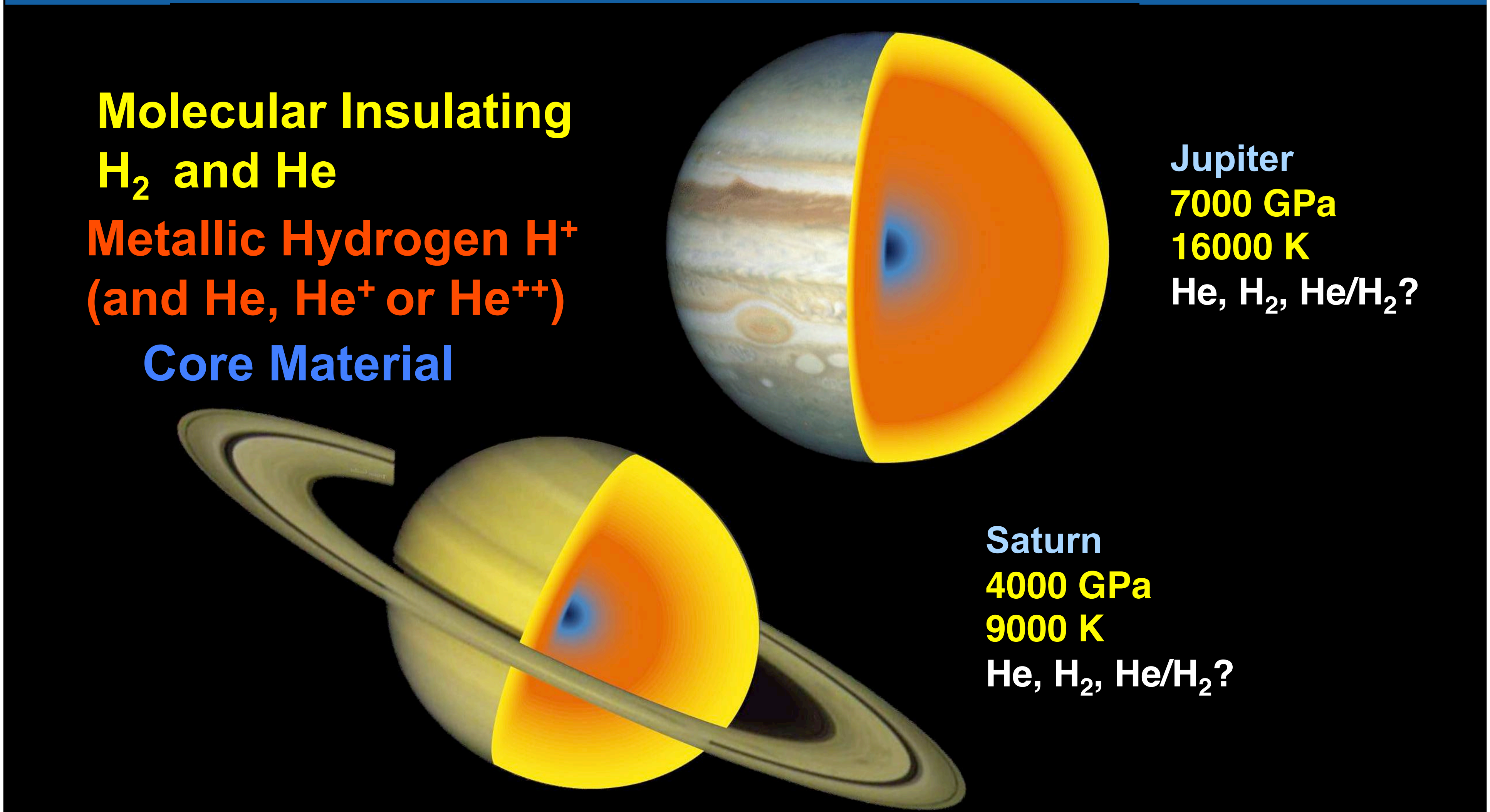
Outline

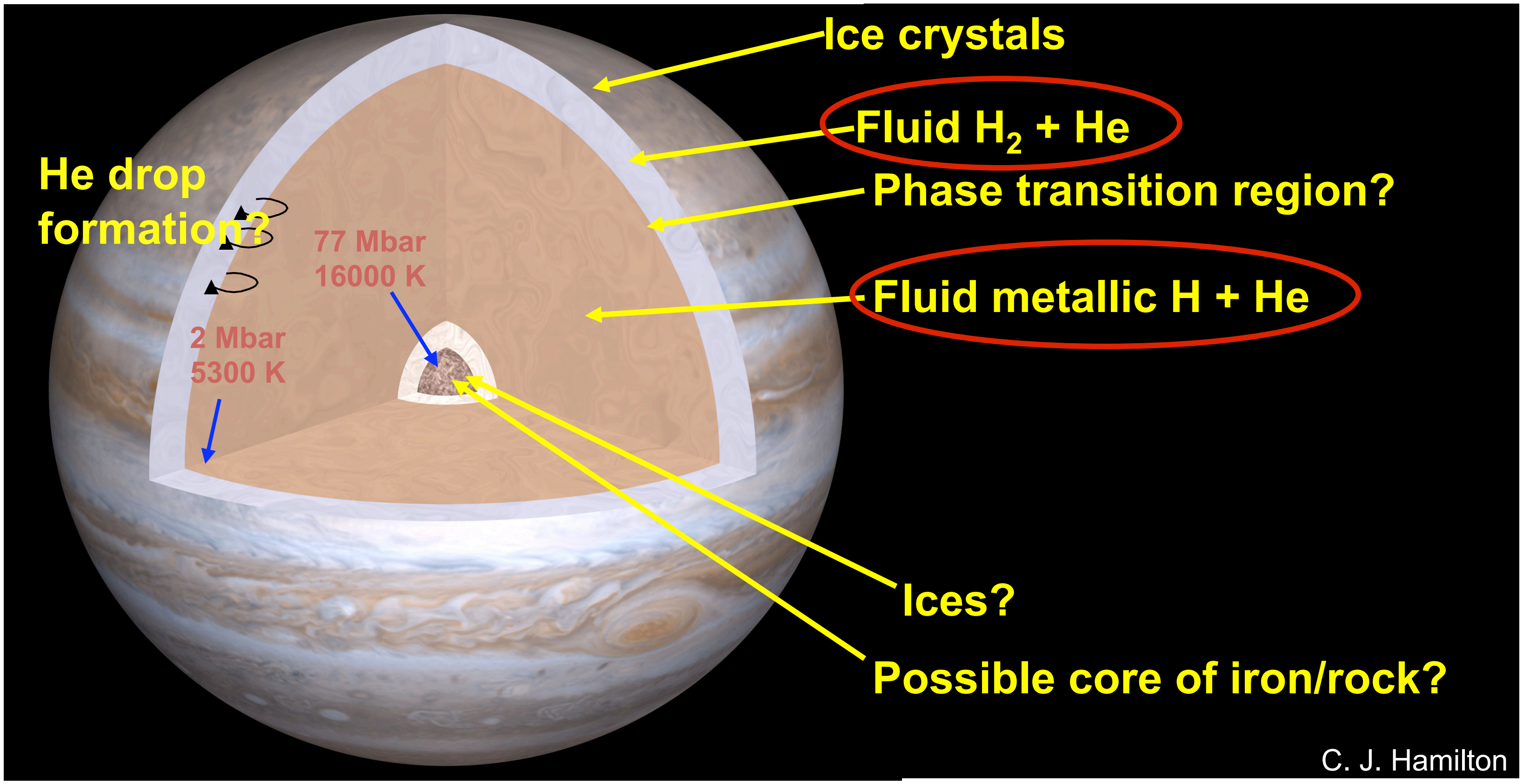
- **Planetary Science Applications**
- **Pre-compressed targets**
- **Helium**
- **Hydrogen/Deuterium**

- **Collaborators:**
- **Peter Celliers, Damien Hicks, Ryan Rygg, Gilbert Collins – LLNL**
- **Stephanie Brygoo, Paul Loubeyre – CEA**
- **Stewart McWilliams, Dylan Spaulding, Raymond Jeanloz – UCB**
- **Tom Boehly – LLE/UR**

Our ultimate goal is to study the core states of giant planets in the laboratory

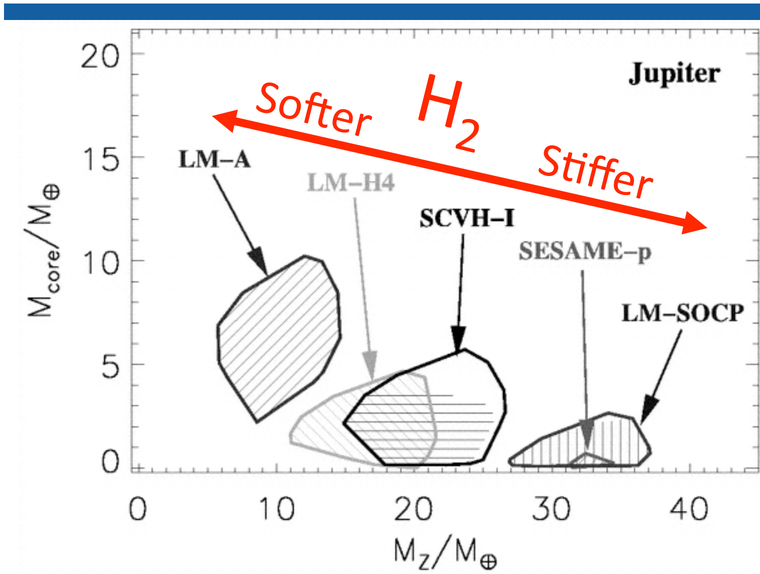


These experiments address outstanding issues in the evolution and dynamics of giant planets.

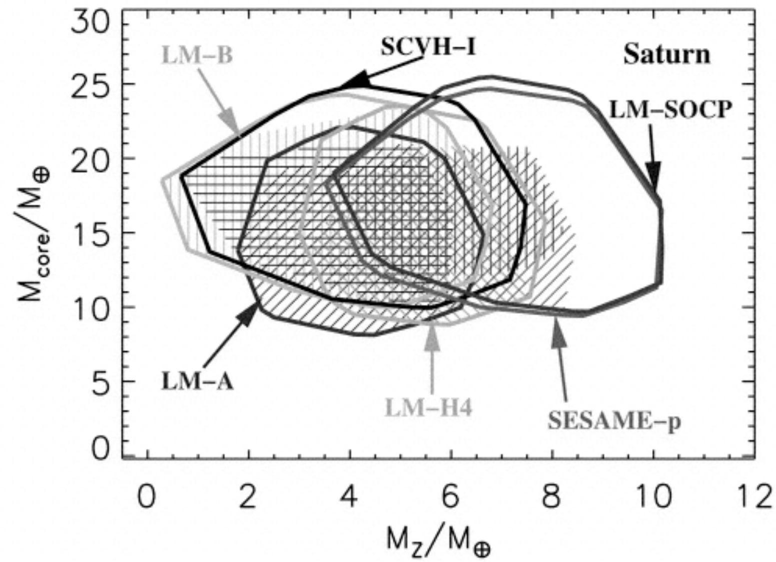


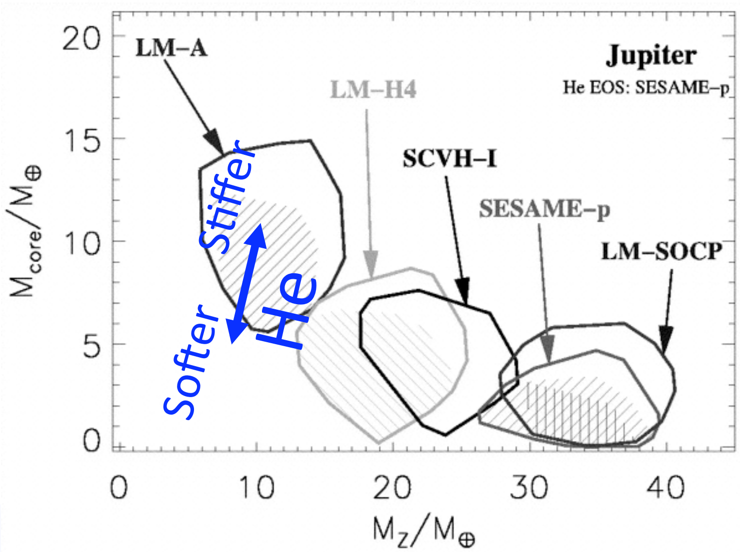
How can we study these light fluids at such high density?
How can we study H_2/He mixtures?

Models for the interior structure of Jupiter/ Saturn are dependent on H_2 and He EOS.



He-SCVH EOS (Soft)





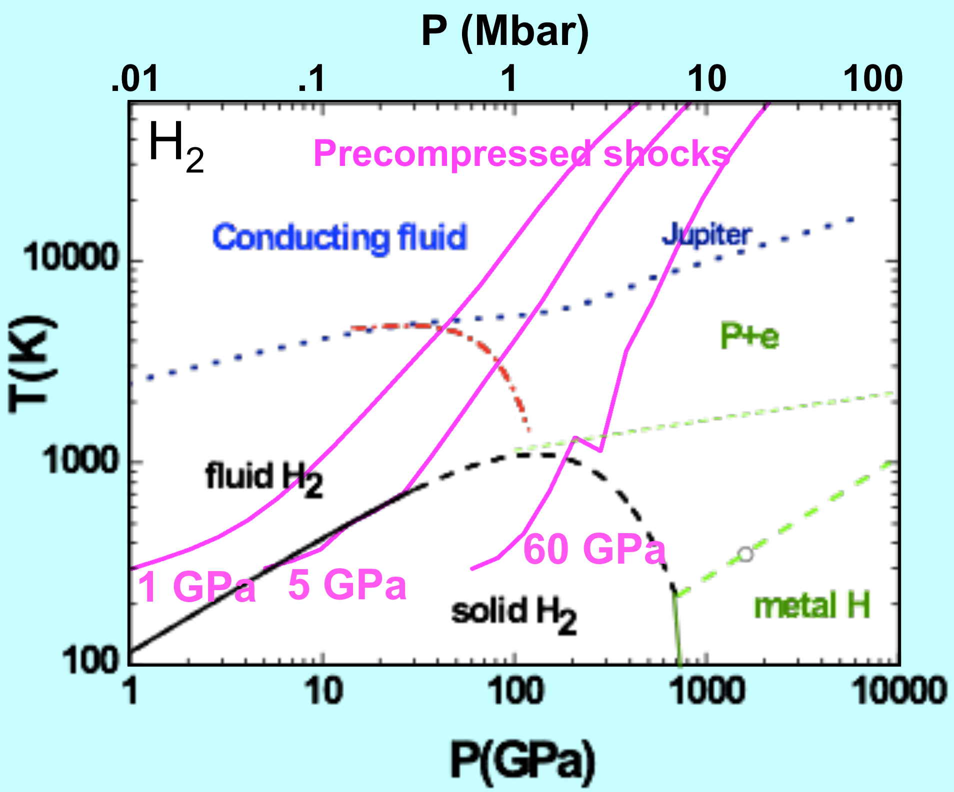
He-Sesame-p EOS (Stiff)

- **Models constrained by R_{eq}, J_2, and J_4**
- **More, better data needed to determine whether Jupiter has a core.**

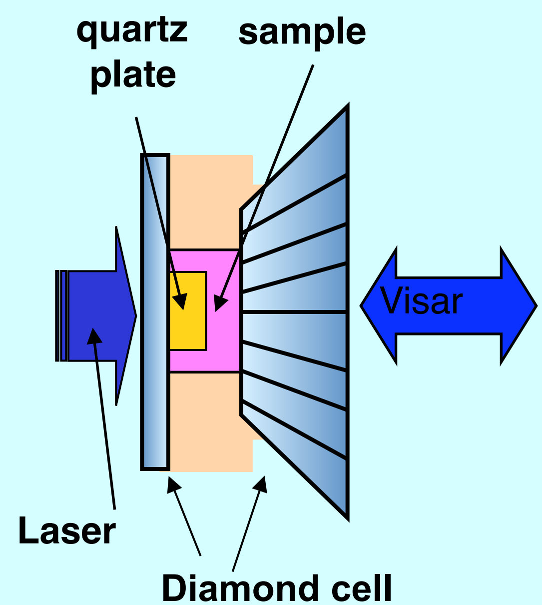
D. Saumon and T. Guillot, Ap. J. 609, 1170 (2004)

Coupling laser shocks with Diamond Anvil Cells (DACs) lowers the Hugoniot temperature for He, H_2, D_2

Pre-compression is used to change the initial density and thus follow different Hugoniots



Pre-compression allows access to these high ρ

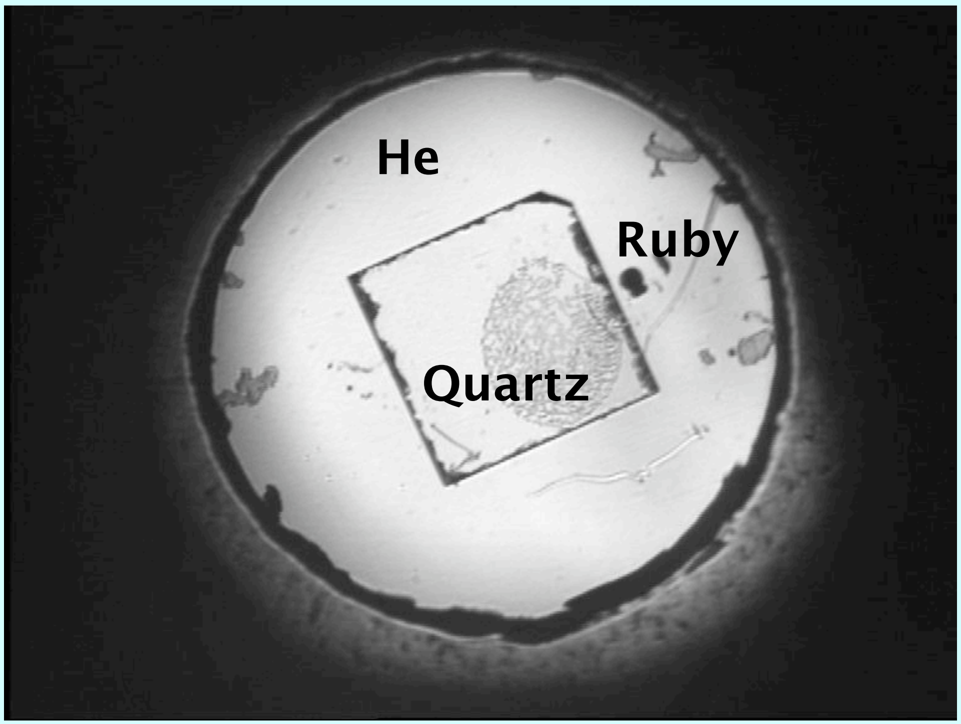


Loubeyre, 06
Jeanloz, PNAS 07

Pre-compressed targets are the *only* way to shock H_2/He mixtures

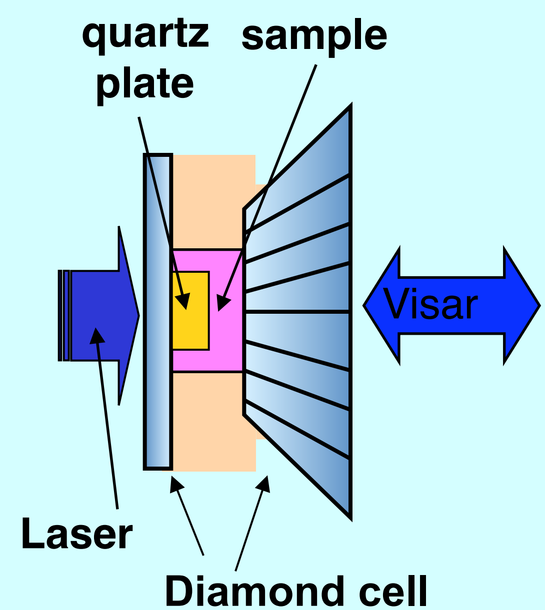
Every target contains a ruby to determine initial compression and a quartz reference plate

Sample of helium and quartz plate through anvil window



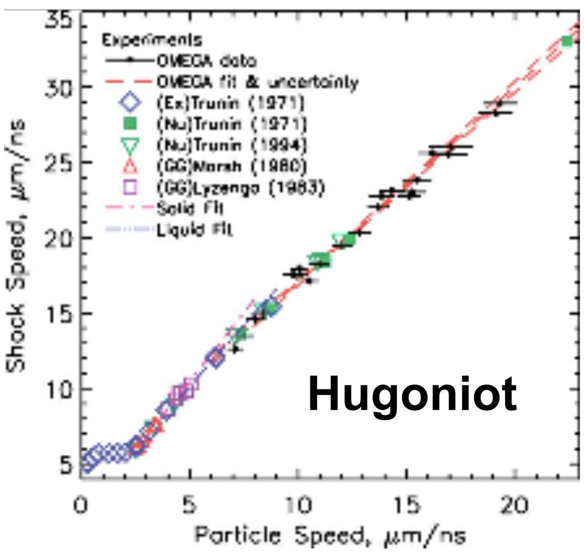
Loubeyre, 06

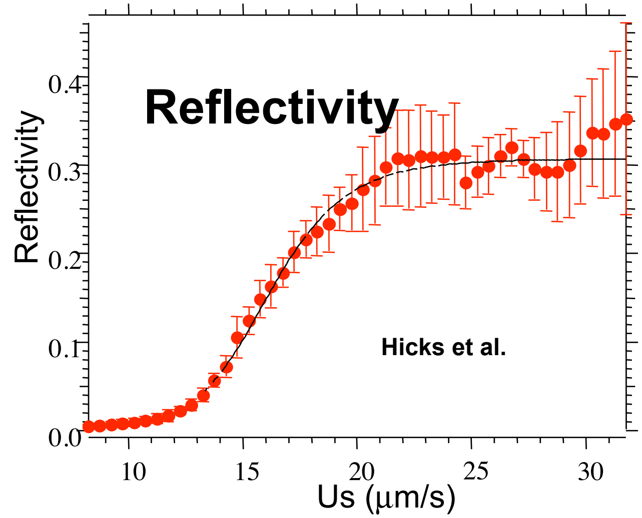
Pre-compression allows access to these high ρ

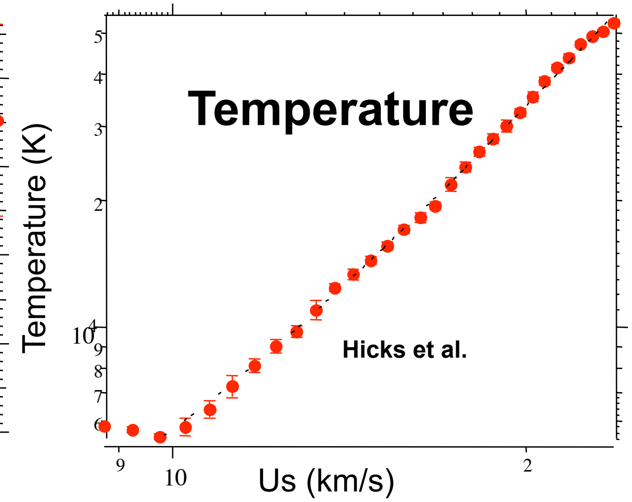


Quartz plate serves as standard for EOS, Reflectivity, Temperature

All of our observables are referenced to a quartz standard





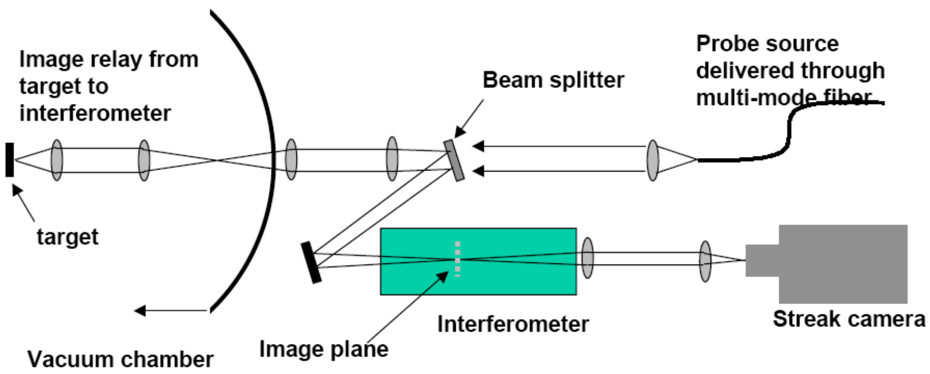


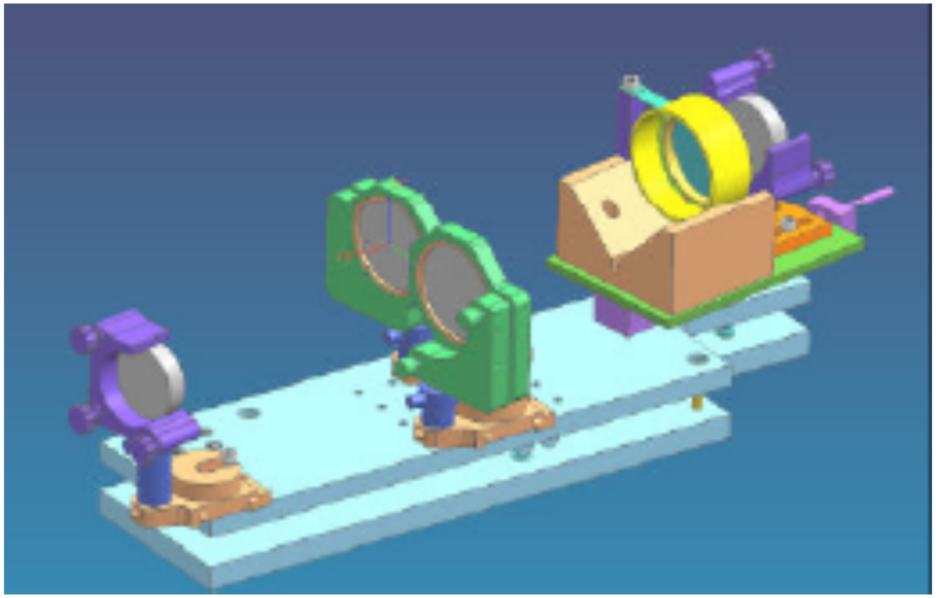
Avantages :

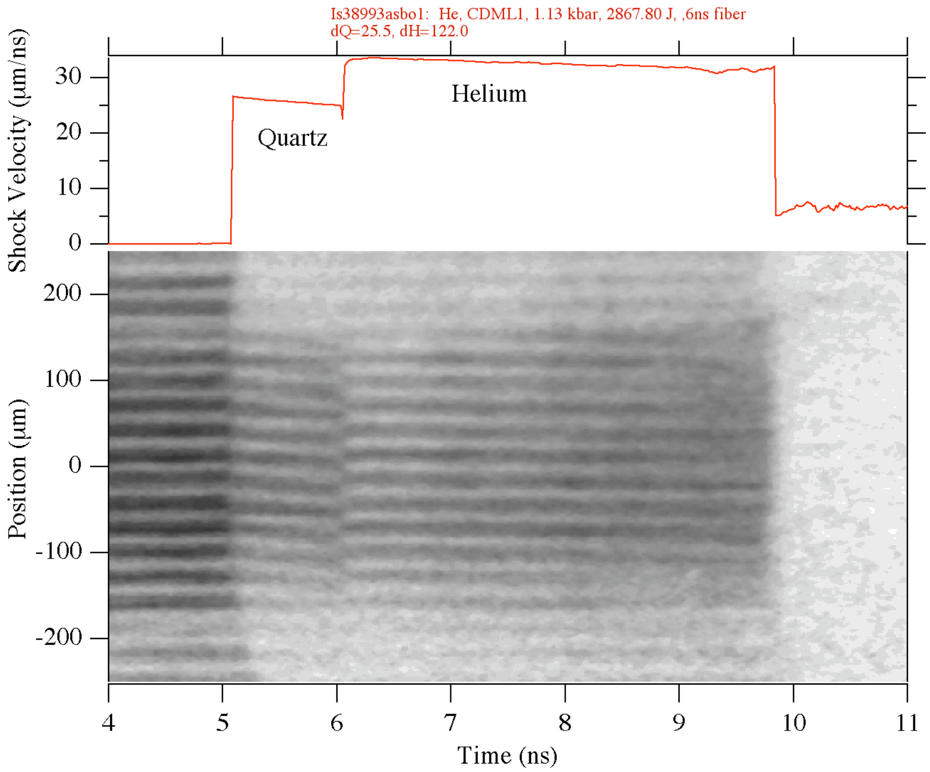
- Reflecting for low Us: VISAR measurements possible
- Hugoniot well defined
- Well caracterized
- Low compressibility and various allotropic forms

Solid quartz is complex, but is always shock-melted in our measurements .
As our understanding of quartz improves, this data will also improve.
Very similar to the ruby pressure scale for DAC experiments.

We use VISAR to measure quartz and helium shock velocities, reflectivity and timing.





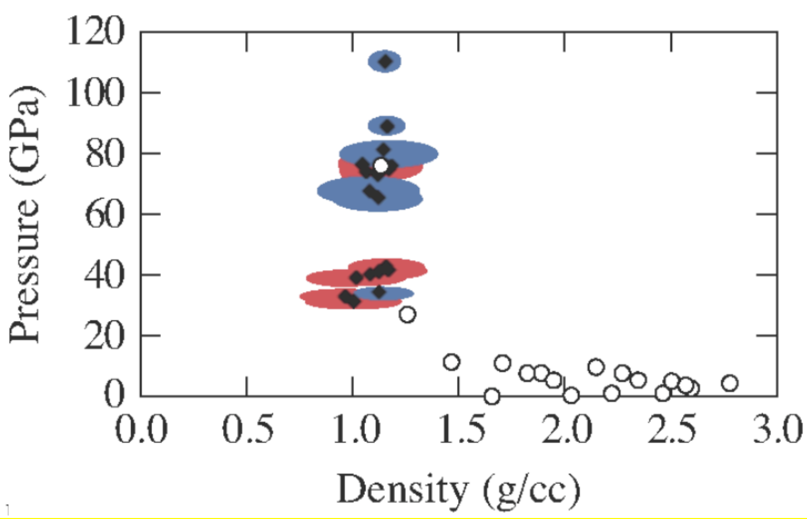


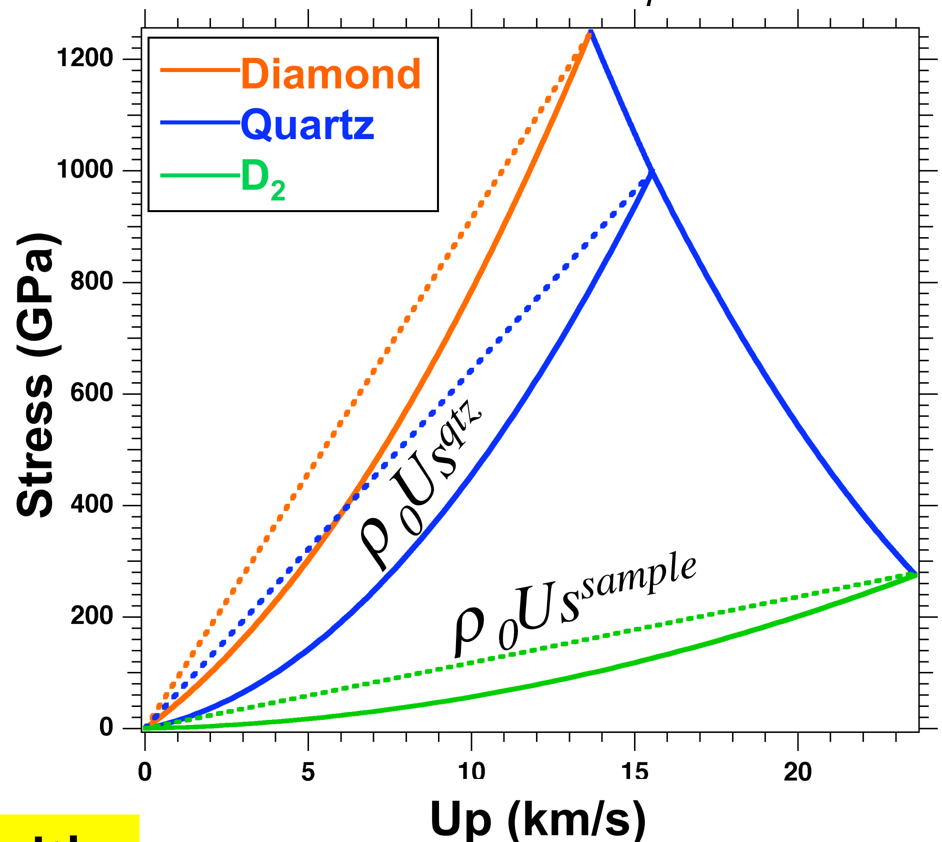
- Impedance matching is performed at the quartz—helium breakout.
- Reflectivity is referenced to quartz at breakout.

We use impedance matching with quartz to determine the shock state

Conservation of energy, momentum, mass give relations across a equilibrated (*not-necessarily planar or steady*) shock: (U_s, U_p, P, ρ, E)

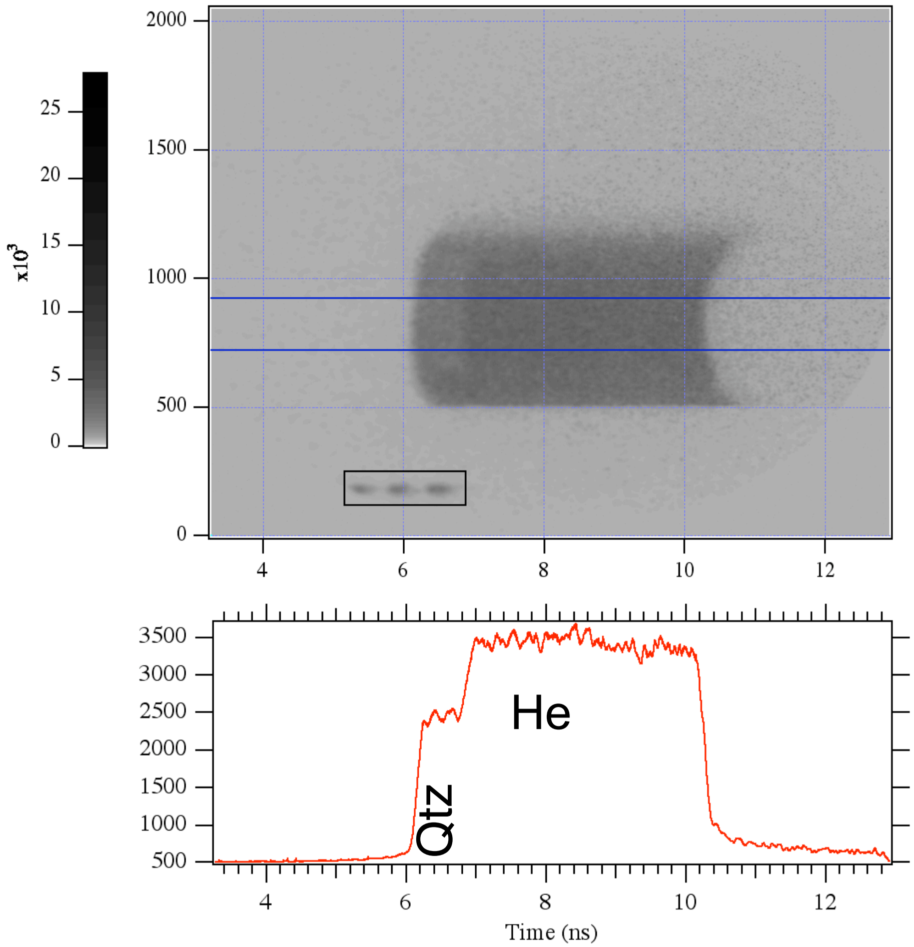
- *We measure Us^{qtz}, and Us^{sample} directly,*
- *Up^{sample} by impedance matching,*
- *R^{sample} and T^{sample} relative to R^{qtz} and T^{qtz}.*

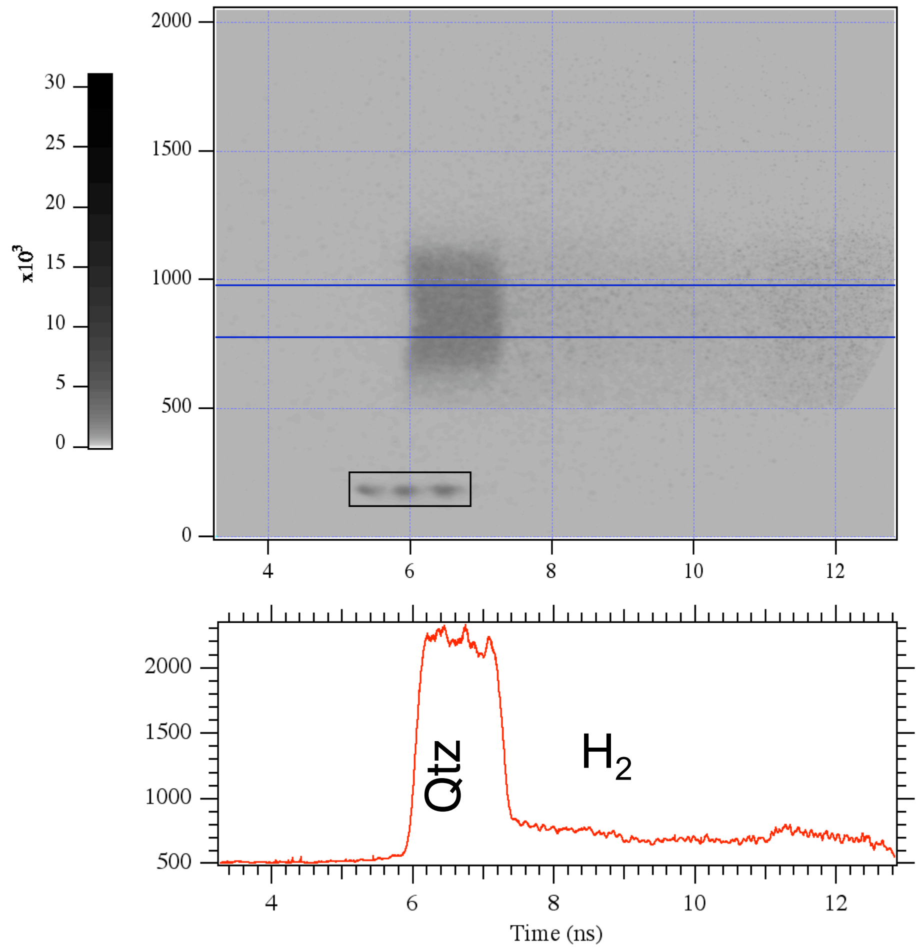




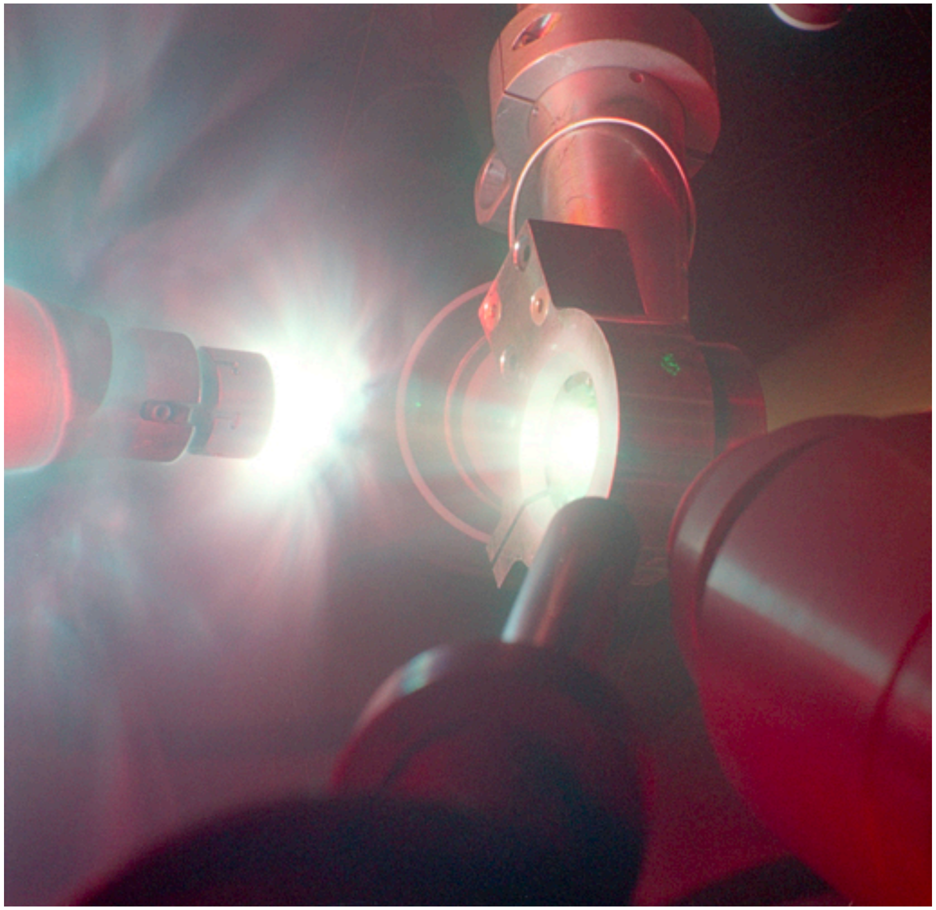
Good agreement on silica aerogel with data from Z –Boehly et al. (2007)

We use an SOP (Streaked Optical Pyrometer) to determine temperature and timing

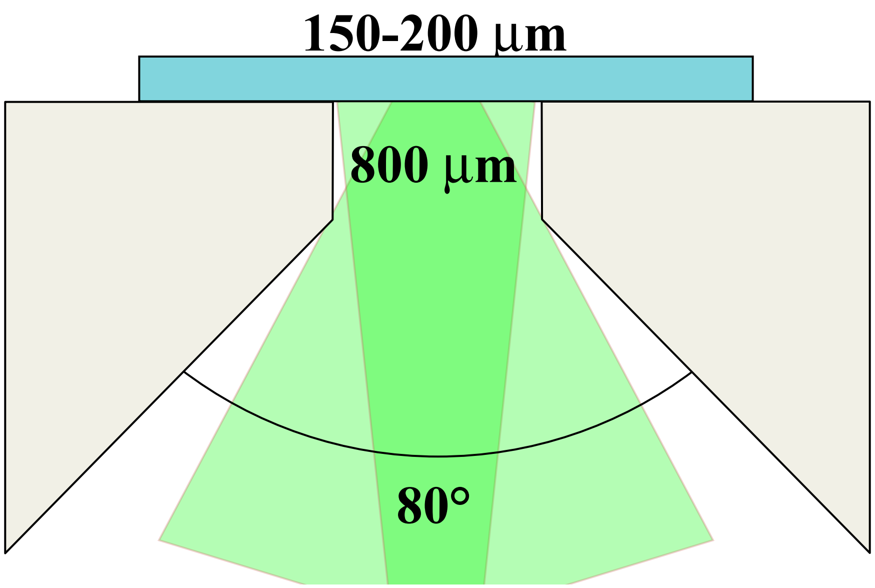




The DAC targets are large and initially generated many high-energy (>100 keV) x-rays and EMP.

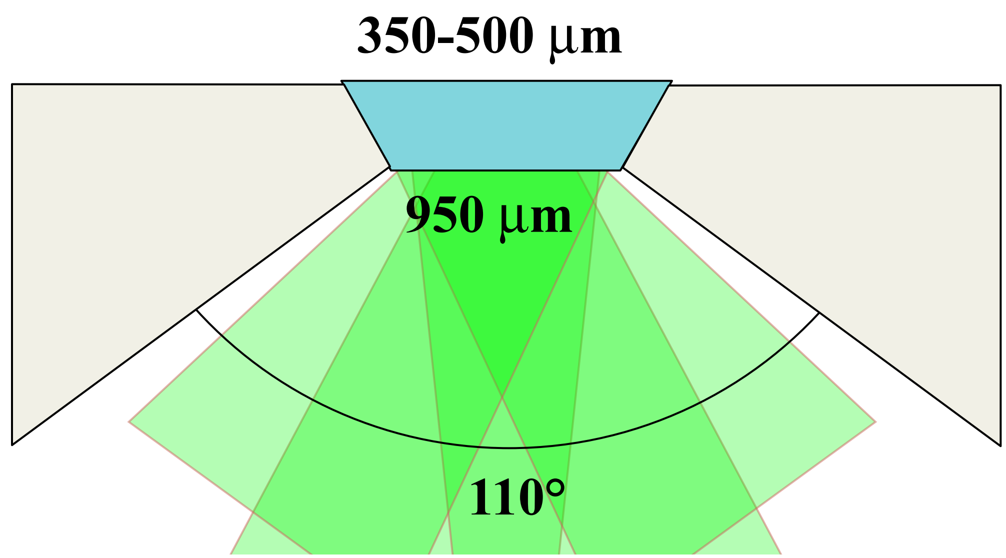


Using Boehler / Almax seats solved long-standing problems with high energy x-rays and EMP



Up to 6 beams or 2850 J

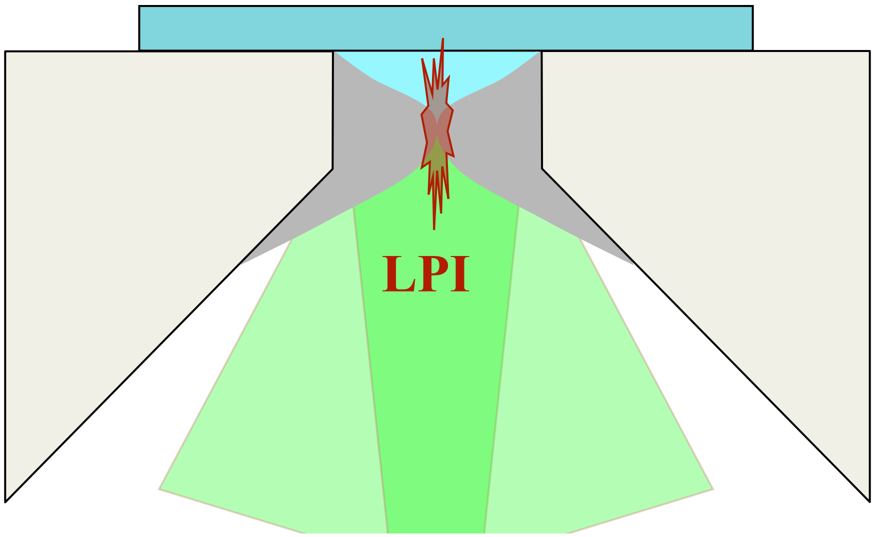
We always have many high energy X-rays (>100 keV) and severe EMP problems when shooting full energy



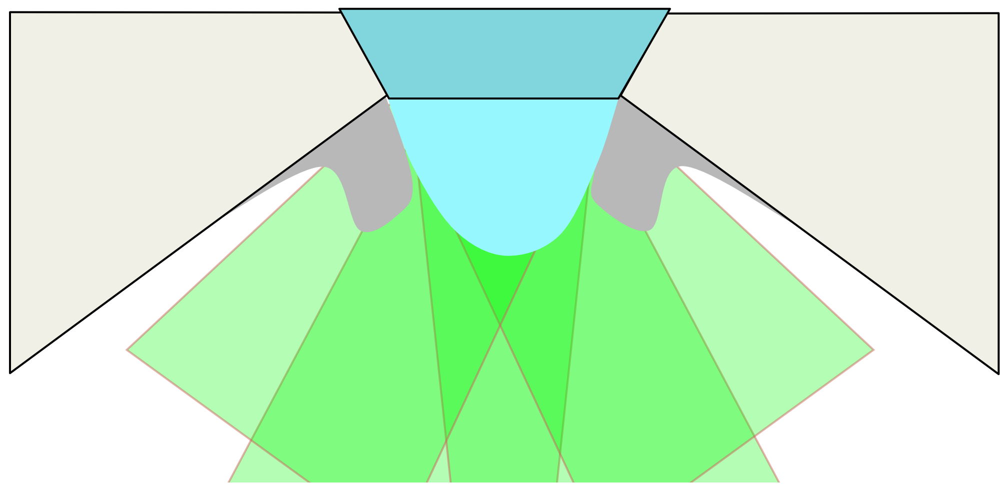
Up to 12 beams or 5700 J

We saw no significant high energy X-rays or EMP problems when shooting full energy.

Using Boehler / Almax seats solved long-standing problems with high-energy x-rays and EMP



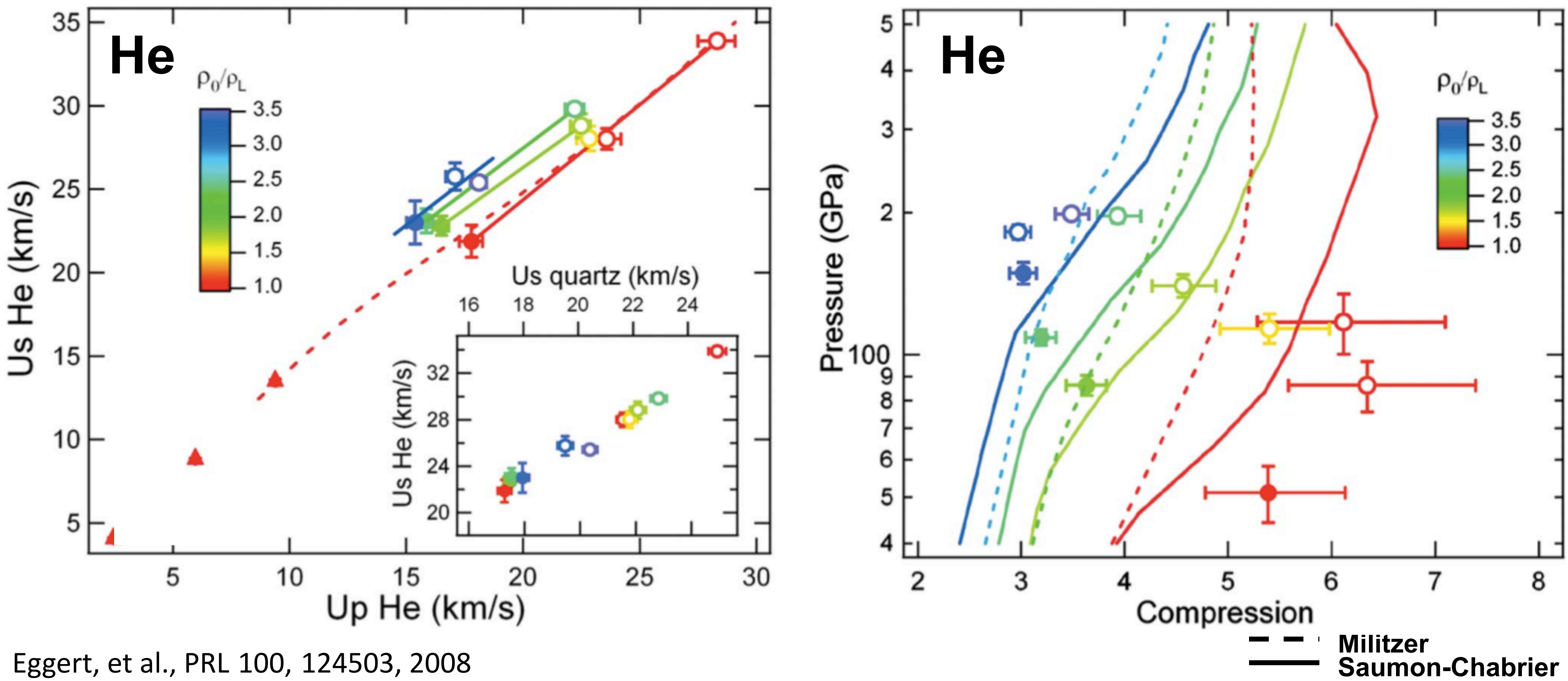
WC support acts like a hohlraum. When the plasma stagnates on axis it becomes very hot and LPI produces high-energy x-rays and EMP



Up to 21beams or 10 kJ

Blowoff from WC supports no longer stagnate on axis and the diamond is able to clear the region. Much lower high-energy x-rays and EMP are observed.

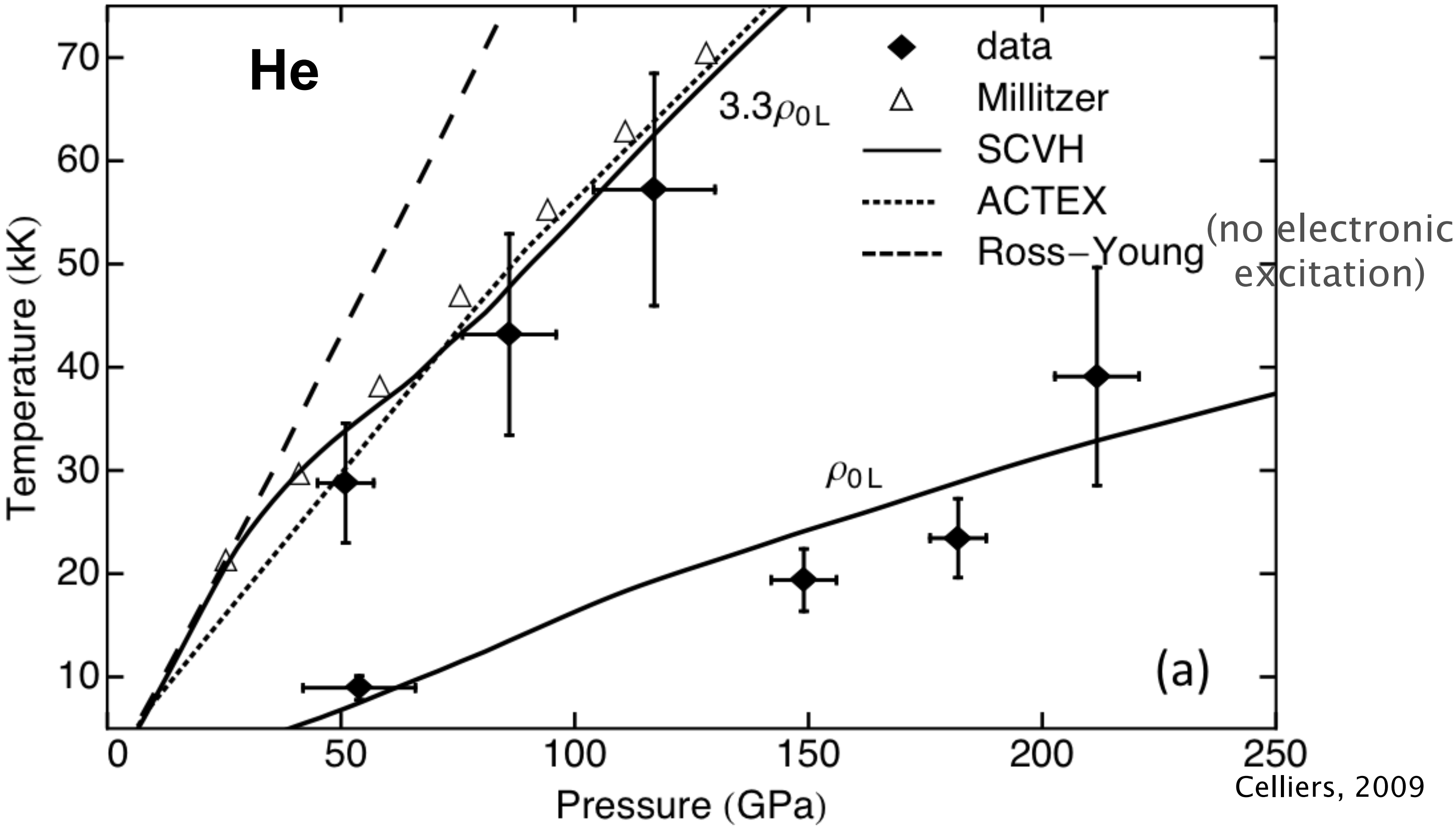
We measured the He Hugoniot for pre-compressions of 1-3.5 times liquid density



Eggert, et al., PRL 100, 124503, 2008

A chemical model fits our data fairly well.

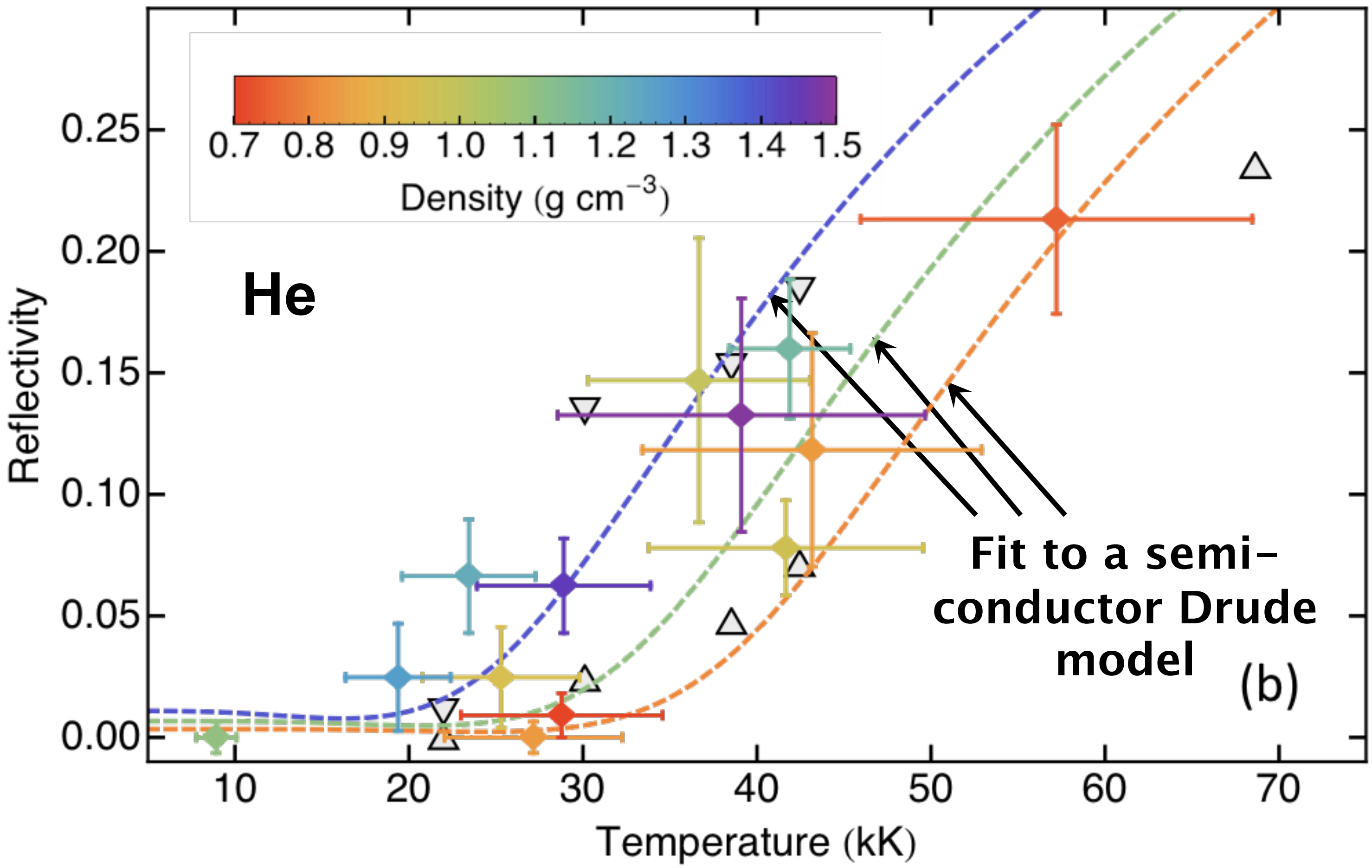
Our temperature measurements agree well with chemical models



Celliers, 2009

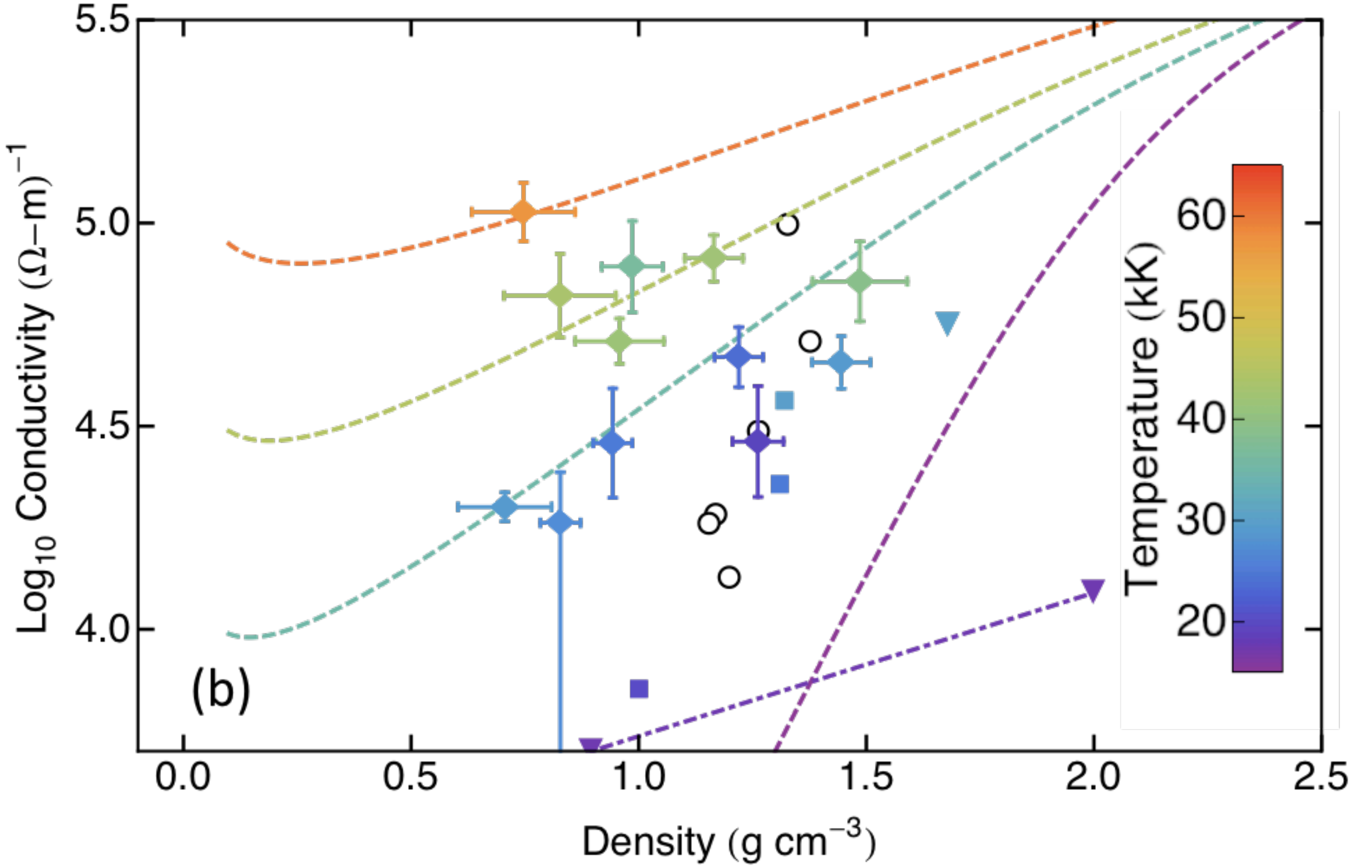
Electronic excitations are clearly necessary for agreement

We observe temperature *and* density effects on the reflectivity



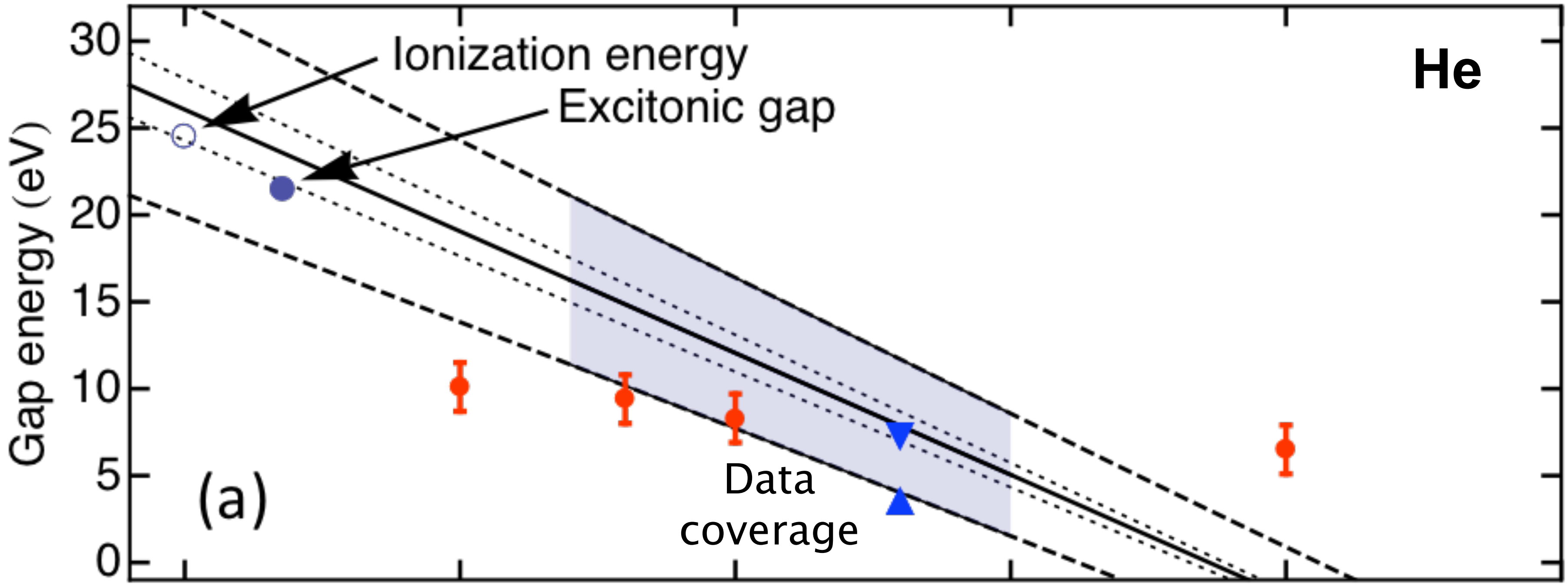
A semiconductor Drude model gives a good fit to the reflectivity data (dashed lines)

We fit the conductivity derived from reflectivity to a semiconductor Drude model



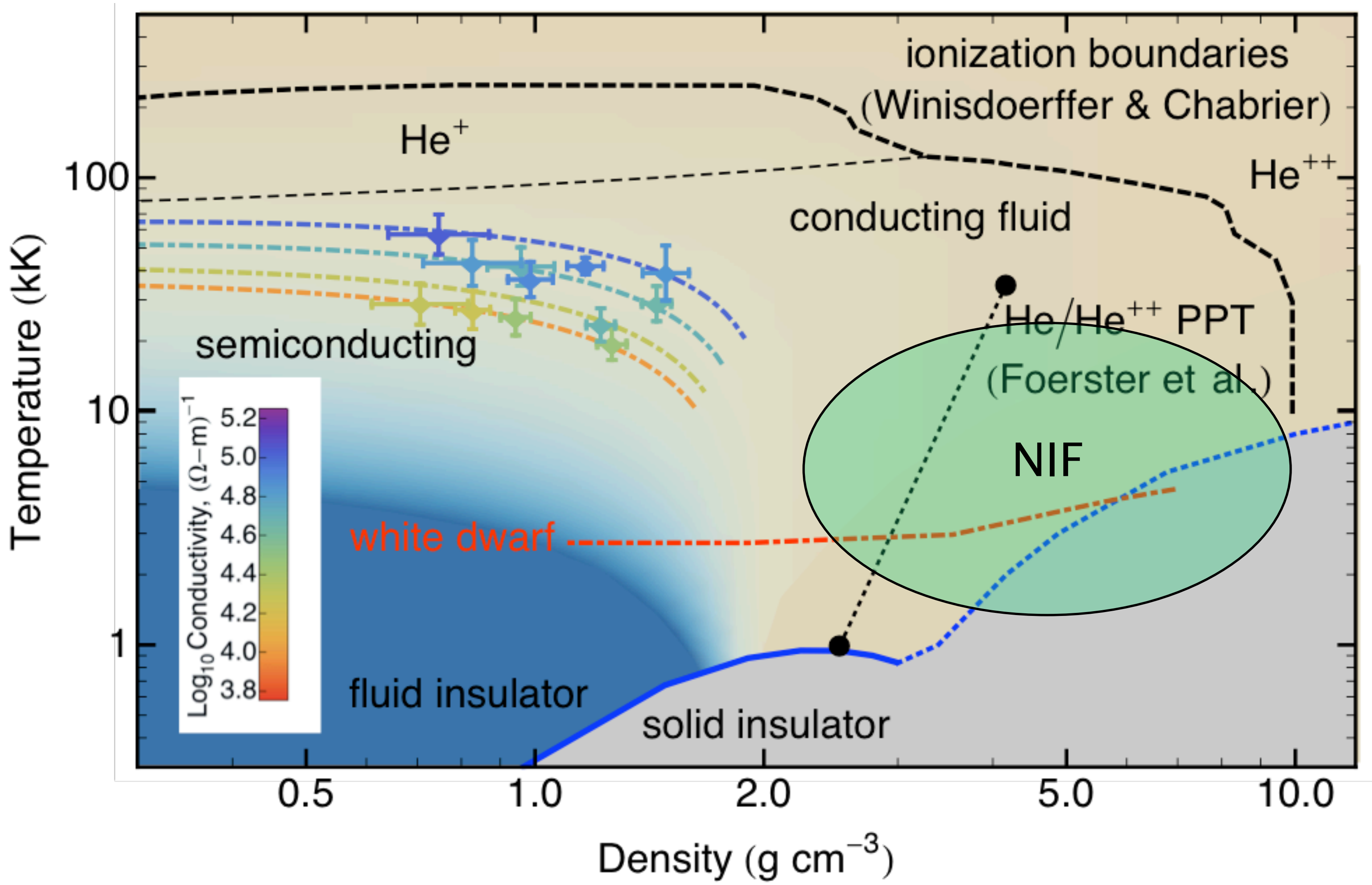
$$\sigma(\omega) = \frac{n_e e^2 \tau}{2 m_{eff}} (1 - i\omega\tau)^{-1}, \quad \text{where,} \quad n_e = \frac{4}{\pi^2} \left(\frac{m_{eff} kT}{2\hbar^2} \right)^{3/2} \int_0^{\infty} \frac{x^{1/2}}{1 + \exp\left(x + \frac{E_g}{2kT} \right)} dx$$

The semiconductor Drude model fit implies band closure

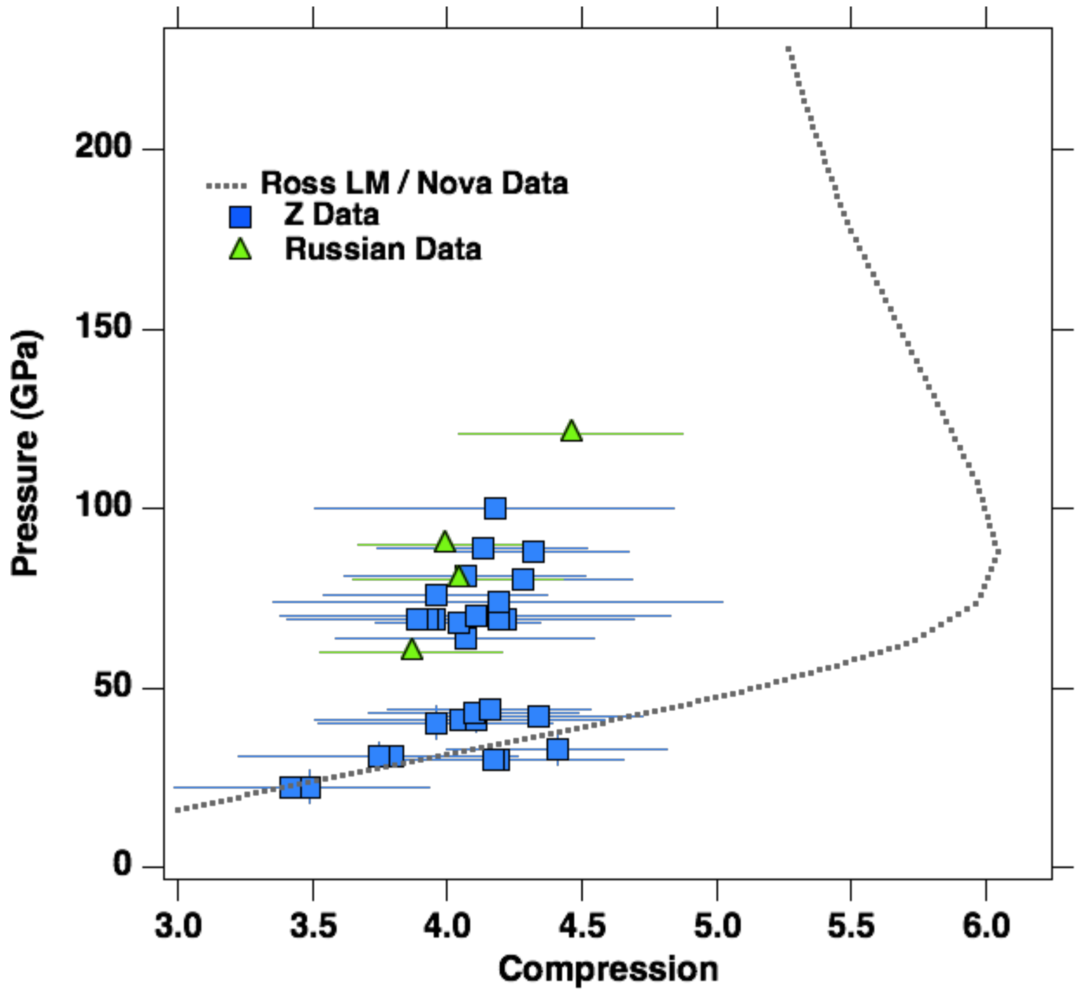


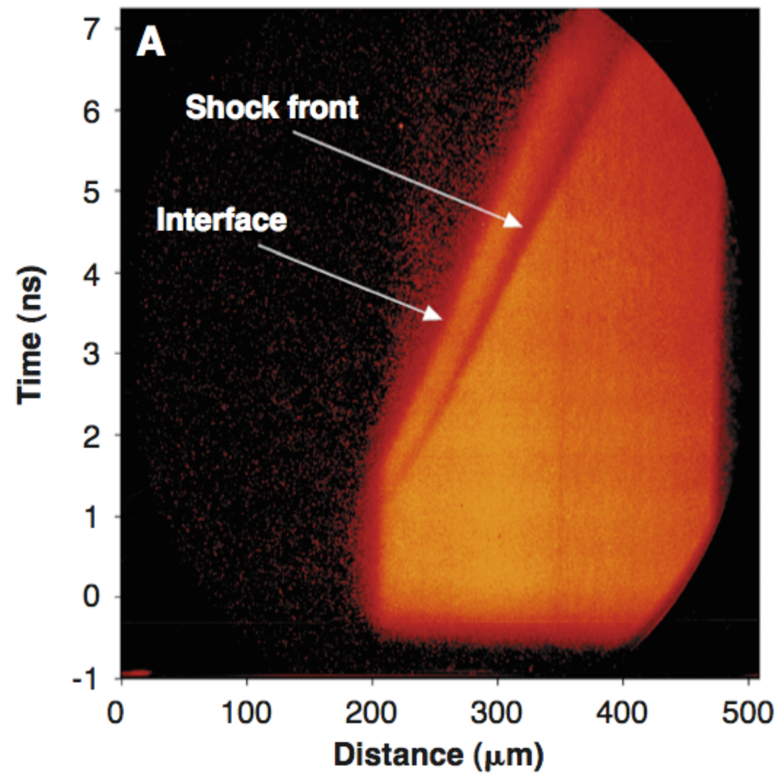
- The quality of the semiconductor Drude model fit found a strong band-gap dependence on density, but not on temperature.
- Gap closure is predicted at 1.8±0.3 g/cc.

Our results suggest that He ionizes earlier than previously thought



There have been some controversies about D_2 Hugoniot experiments

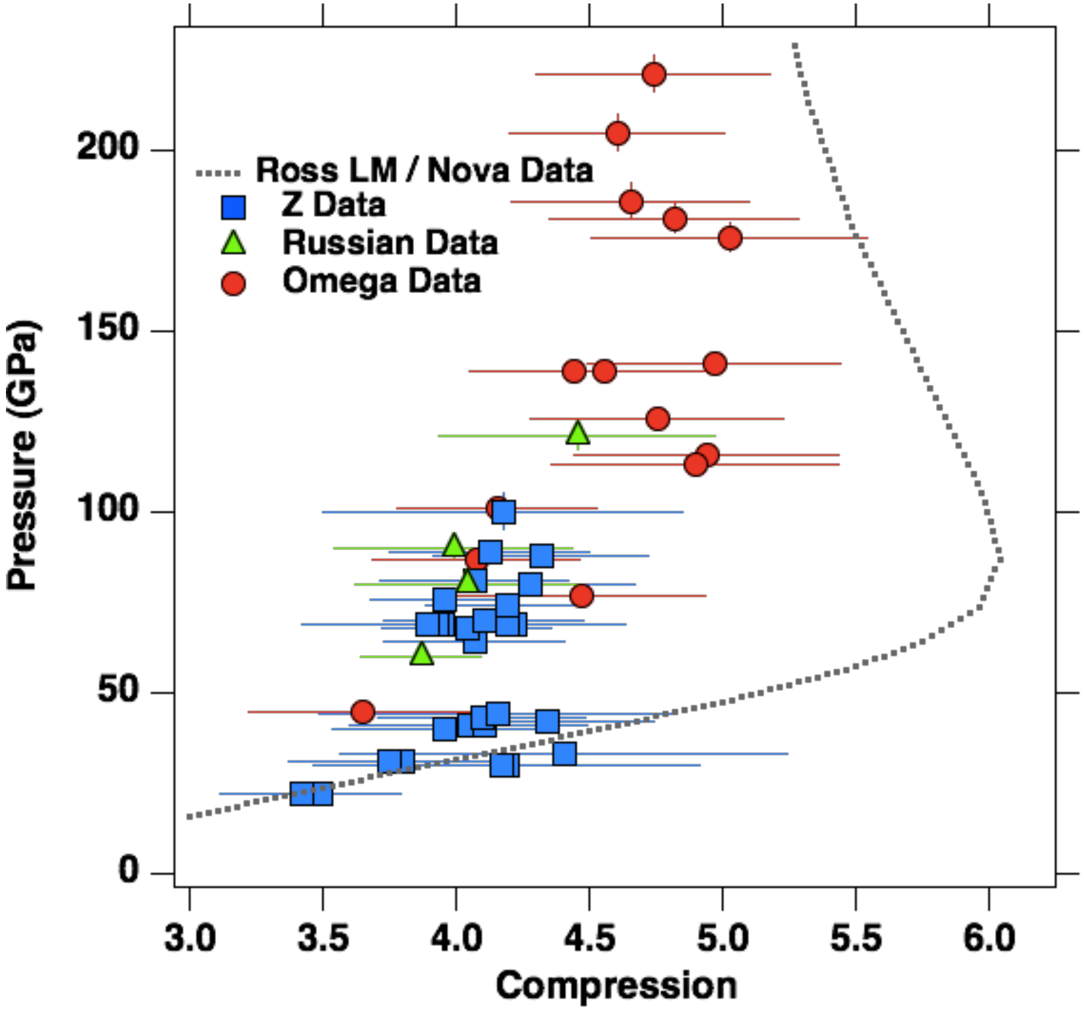




Collins, et al., Science, **281**, 1178 (1998)

Initial Nova absolute-Hugoniot data agreed with Ross's LM model. Impedance match data at Z and in Russia disagreed.

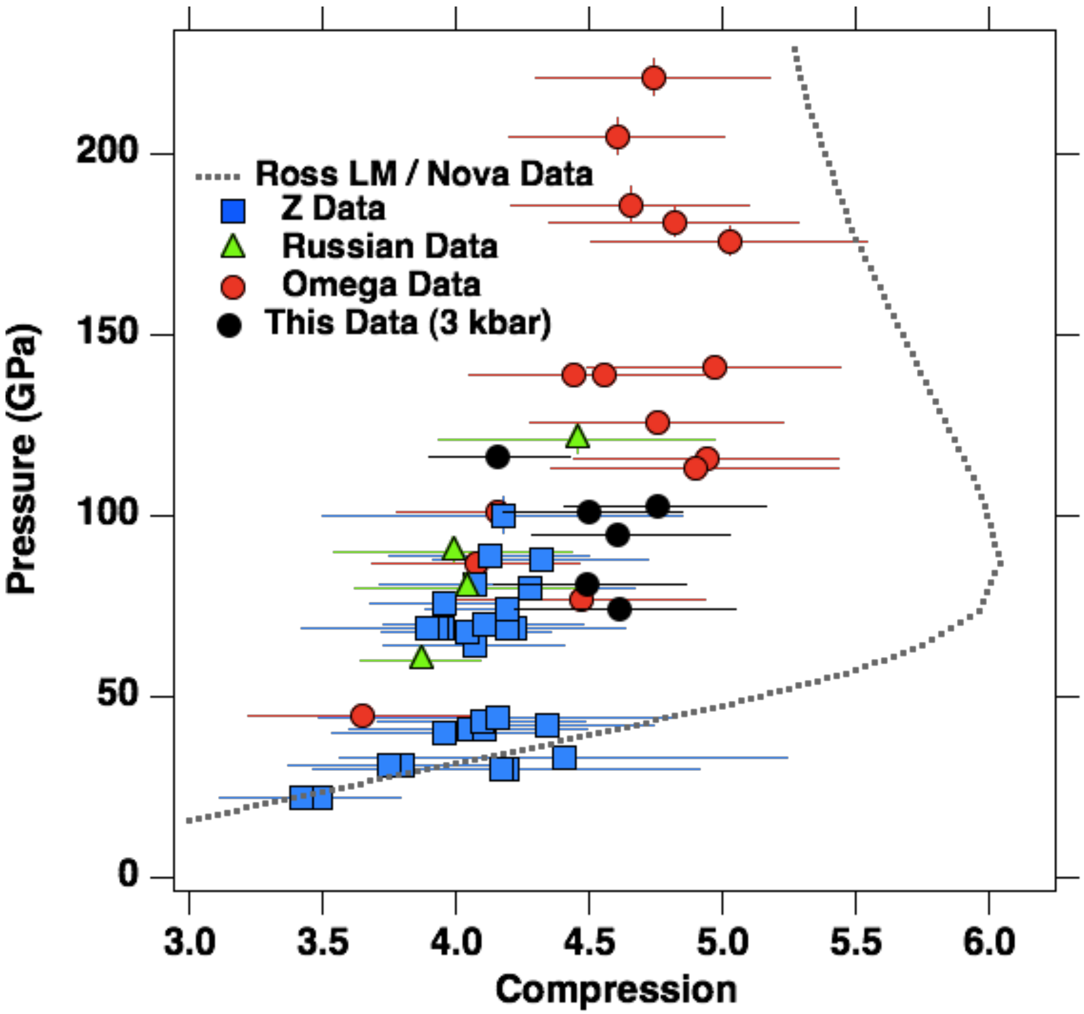
There have been some controversies regarding the D_2 Hugoniot



New Omega data using aluminum impedance match restores agreement between data sets

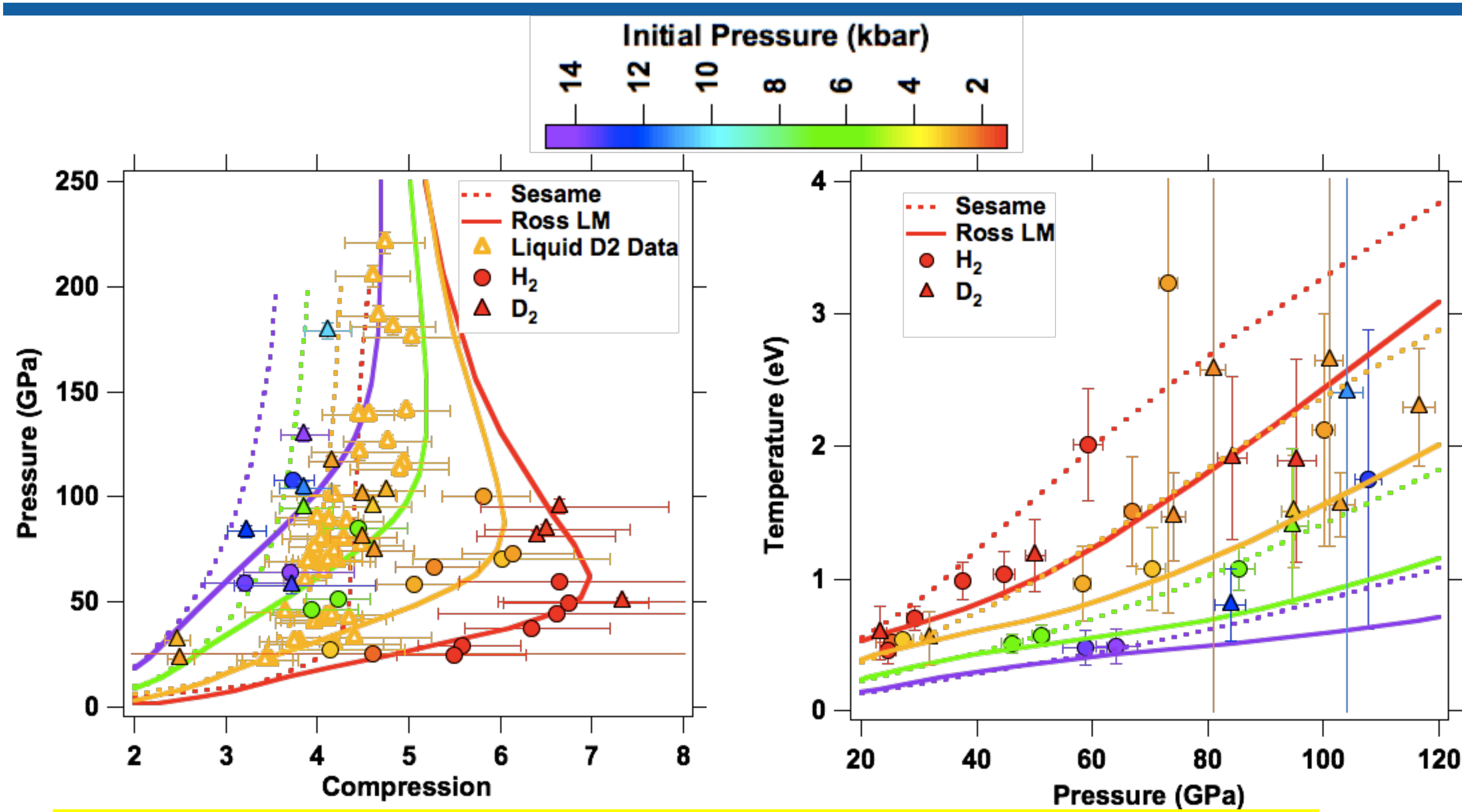
Hicks, et al., PRB **79**, 014112 (2009).

There have been some controversies regarding the D_2 Hugoniot



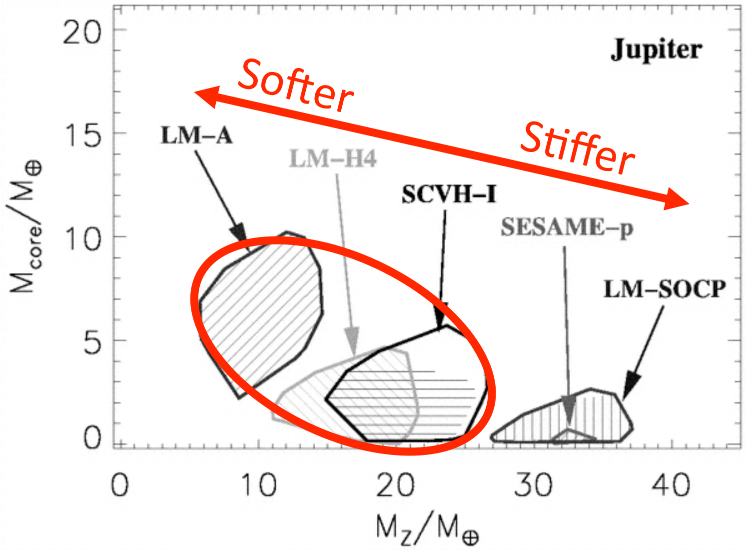
- Our data is for liquid-density D_2 is consistent with existing data.
- Quartz impedance match appears OK for D_2.

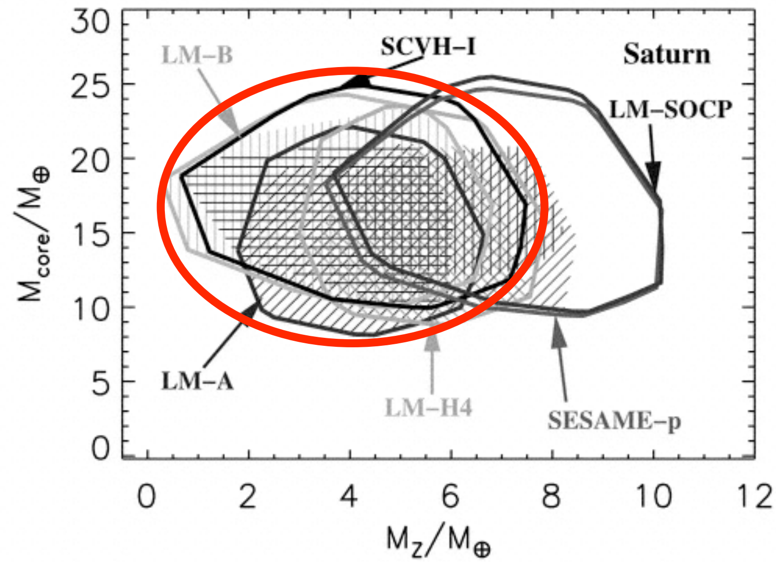
Our preliminary results for H_2 and D_2 suggest that a soft hydrogen EOS fits the data better.

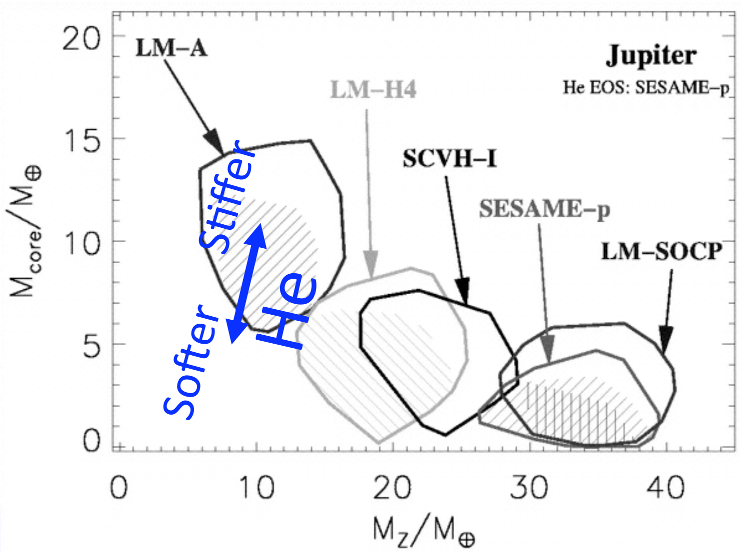


We are currently performing internal consistency checks on our results.

Models for the interior structure of Jupiter/Saturn are dependent on H_2 and He EOS.





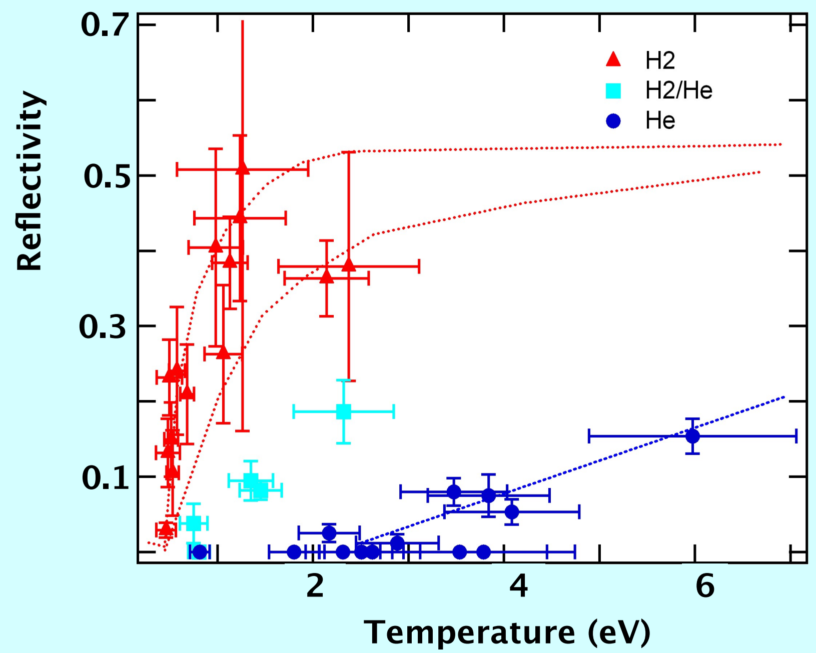


- **Our data appears to favor a soft EOS for both H_2 and He.**
- **These models favor partitioning of heavy elements into a relatively large core in Jupiter.**

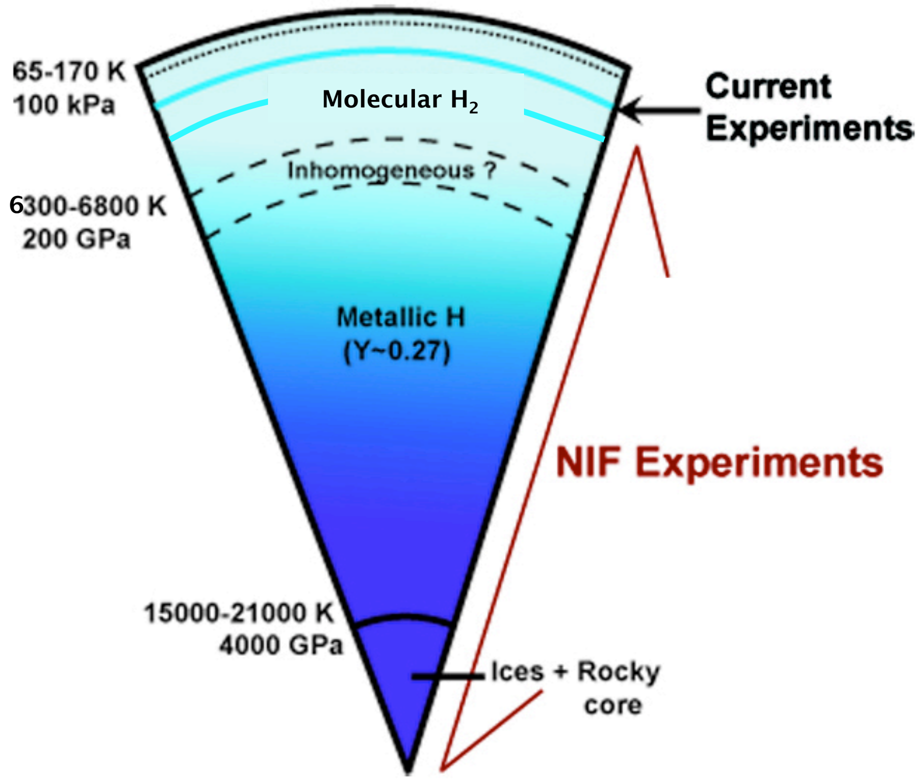
D. Saumon and T. Guillot, Ap. J. 609, 1170 (2004)

First He/H2 experiments pave the way for understanding the most extreme states of giant planets

Reflectivity and T for He/H2 mix is between He and H2



Data and theory suggest He/H2 likely miscible at 1 Mbar/30kK



Precompression is the only way to study He/H_2 mixtures

Summary

We have proposed, used, and validated (using aerogel and D_2) quartz as an impedance-match standard

We have collected extensive EOS data on He, D_2, and H_2 at conditions relevant to giant planet interiors.

We observe relatively soft EOS's for all three materials

We observe temperature-induced ionization in He

Our analysis indicates a strong electronic-gap density dependence

Our results favor planetary models for Jupiter that include partitioning of heavy elements into a relatively large core